Extended Abstract
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SRTM Mast Damping Subsystem Design and Failure Investigation

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1. Introduction

The Space Radar Topography Mission (SRTM) flew in February 2000 on the space shuttle Endeavor as the primary payload for STS-99. The objective of this joint project between the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA) is to generate a near-global high-resolution database of the earth's topography. This mission made use of Interferometric Synthetic Aperture Radar (ISAR) to digitally survey the earth's surface from space. The primary product of this 11-day mission a topographic database of 80% of the earth's land surface, i. e. most land surfaces between ± 60° latitude. The resulting digital terrain data set provides a significant improvement over currently existing global topography data sets.

1.1 Instrument Overview

The SRTM architecture is based upon the Spaceborne Imaging Radar/X-band Synthetic Aperture Radar (SIR-C/X-SAR) instruments which flew twice on the Space Shuttle Endeavor in 1994, see Jordan et al, 1995. The SIR-C/X-SAR project was a collaborative effort between NASA, which developed SIR-C, and the German and Italian space agencies, which developed X-SAR. The SIR-C instrument was two separate SAR's which operate in the C, and L-bands. The X-SAR instrument operates in the X-band. The combined SIR-C/X-SAR instruments including electronics essentially fill the shuttle payload bay. The primary objective of the SIR-C/X-SAR missions was the radar imaging of a select " supersite" targets. SIR-C/X-SAR's secondary objectives, which enabled SRTM, included the demonstration of repeat pass interferometry and scan-SAR. The repeat pass interferometry data is then used to recover the topographical features of the target surveyed. While scan-SAR is a method of beam steering which is employed by SRTM, in the C-band, such that the radar swath width is sufficient to achieve complete mapping coverage in 159 orbits. See Rosen et al for a detailed treatment of Synthethic Aperture Radar Interometry.

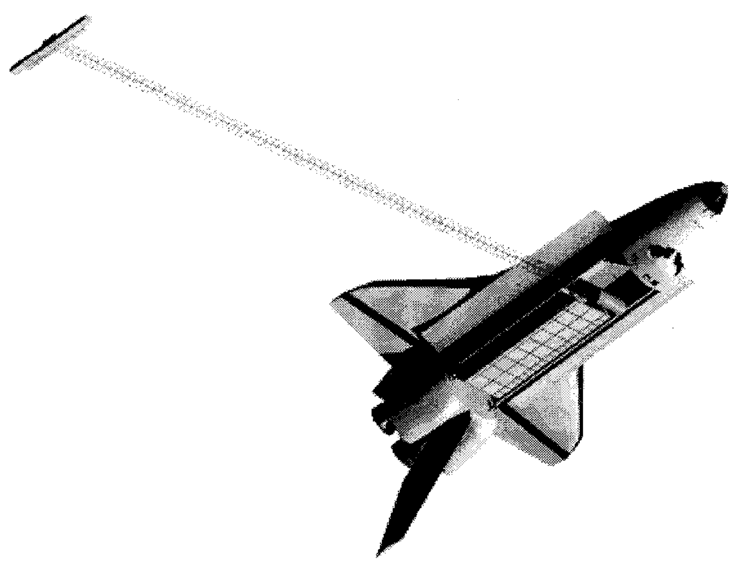

Figure 1. SRTM Mission Configuration

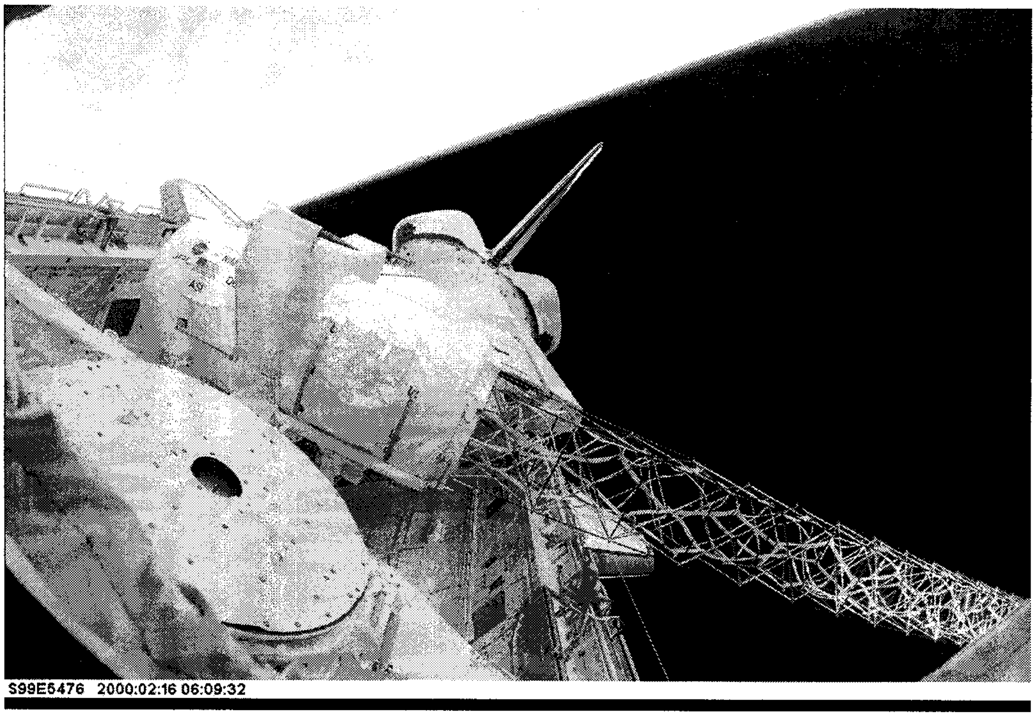

Figure 2 Deployed Mast Configuration

The required modifications to the existing radar instrument to collect the interferometric data included a second C-band antenna, a 60-meter mast, metrology, and additional avionics. Further, the German Space Agency provided a second X-band antenna. The fundamental SRTM instrument configuration is illustrated in figure 1. Simplistically, SRTM makes use two radar apertures separated by a fixed distance, or baseline, to form a fixed baseline interferometer. The in-board aperture, relative to the Orbiter payload bay, is used to both send and receive radar energy while the outboard antenna only receives energy.

One of SRTM's significant features is the use of a 60-meter long deployable mast that serves to deploy an outboard antenna and creates a stable baseline. The 60-meter deployable truss and its deployment mechanisms are described by Gross and Messner. A photograph of the deployed mast is shown in figure 2. The structural dynamic issues associated with a 60-meter mast and large tip mass, i. e. the outboard antenna, deployed from the Shuttle required significant attention during the design and implementation of SRTM. The specific topic covered herein; include the design and testing of the mast vibration damping subsystem. Further, the mast vibration damping subsystem failed on-orbit, the failure diagnosis that occurred in real time during the mission, and the post mission failure investigation is discussed.

1.2 Mast Vibration Damping Subsystem Description

A mast vibration damping subsystem was added in order to meet mast tip dynamic motion requirements. Specifically, a requirement was levied that the maximum mast tip motion rates be less than 6 cm/sec, and that the mast tip motion be less than 6 mm/sec for ten percent of the time during mapping operations. These requirements were driven by the capability of the metrology system employed to track mast tip during mapping operations. The mast damping mechanisms were designed to achieve high, i. e. greater than 10%, damping ratios in the deployed mast first bending modes and the first torsional mode. Conceptually, the approach employed towards the design of the mast damping system was to concentrate sufficient modal strain energy at the mast interface to the inboard antenna such that only a few localized damping elements can efficiently damp the mast. What this means is that the structural elements which connect the mast to the ~~to~~ inboard antenna structure were softened, i. e. their stiffness was reduced, such approximately half the modal strain of the deployed system's first modes of vibration was concentrated at these elements. The structural attachment of the mast to the inboard antenna structure is shown in figure 3, this structure was called the canister attachment truss (CAT). The CAT is a kinematic, i. e. statically determinate, structure which serves to the mast, and the mast canister to the inboard antenna structure. The CAT forward bipod and the CAT axial strut form a rigid tripod with a monoball, or spherical bearing, at its vertex. The monoball located at the vertex of this rigid tripod can then as a fixed rotation point about which the entire deployed mast can rotate about as a rigid body. The attitude of the mast relative to its fixed rotation point is controlled by the aft bipod, and the vertical strut. The mast damping elements were located at the aft bipod, and the vertical strut. The damping elements located in the aft bipod controlled the mast's first two orthogonal bending modes, while the damping element located in the vertical strut controlled the mast's first torsional mode.

Two different damping mechanisms were developed for SRTM. The bending mode damping mechanism is shown in figure 4, this mechanism is also the CAT aft bipod. Further, the aft bipod upper strut is rigid while the lower strut contains the relatively soft springs and viscous damping elements. The viscous damping elements are mechanically in parallel with the springs. Additionally, a caging mechanism is employed to lock out the soft springs for launch and landing. The torsional mode damping is also the CAT vertical strut. The torsional mode damping mechanism is similar to the bending mode damper, but uses only one damping cartridge rather than three. The damping cartridge employed in both mechanisms is illustrated in figure 5. The three damping cartridges used in the bending mode damping mechanism were filled with a 100 cSt silicone fluid, while the damping cartridge used in the torsional mode damping mechanism was filled with 10 cSt silicone fluid.

2. On-Orbit Failure

As part of the SRTM on-orbit checkout procedure, flight rules required that the natural frequencies of the deployed mast's first vibration modes be measured. The rationale behind this requirement is that the stability of the Shuttle's reaction control system is assured by proper placement of and sizing of notch filters which then serve to mask low frequency dynamics. This system identification was performed with the dampers locked, and unlocked. Additionally, the system identification was also performed for both high and low level excitation. Based on comparison of the system identification results from the dampers locked versus unlocked tests it was concluded the dampers were inoperative. The dampers were re-locked, and the mission continued to a successful conclusion. Proper instrument operation was achieved without functional dampers by utilizing overlapping design performance margin contained within the other SRTM sub-systems.

3. Failure Investigation

Following the mission a failure investigation was conducted in order to determine the root cause of the SRTM damping mechanism failures. The conclusion of this investigation was that both damping assemblies failed due to a common mode failure attributed to the damping cartridge mechanical design. Specifically, it was found that all damping cartridges assembled for SRTM had seized. The SRTM damping cartridge seizure was traced to a dimensional interference between the piston rod outside diameter and the linear bushing inside diameter. It was further determined that the inside diameter of the linear bushing, made from Torlon, had changed dimensionally; i. e. the ID had reduced, thereby eliminating the required clearance between the bushing and piston rod. The two possible physical mechanisms which explain the temporal instability of the bushing inside diameter are: a) silicone fluid absorption by the Torlon linear bushing and b) long term creep of the Torlon linear bushing due to residual stress.

4. Acknowledgments

The effort described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

5. References

D. Gross, and D. Messner, 1999. "The Able Deployable Articulated Mast – Enabling Technology for the Shuttle Radar Topography Mission," *Proc. of the 33rd Aerospace Mechanisms Symposium,* NASA/CP-1999-209259, Pasadena, CA, pp. 15-30.

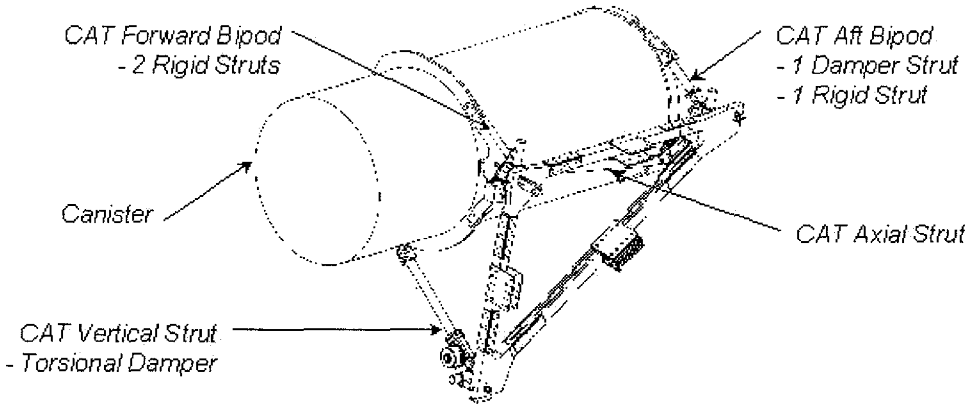

Figure 3 Mast Canister and Canister Attachment Truss

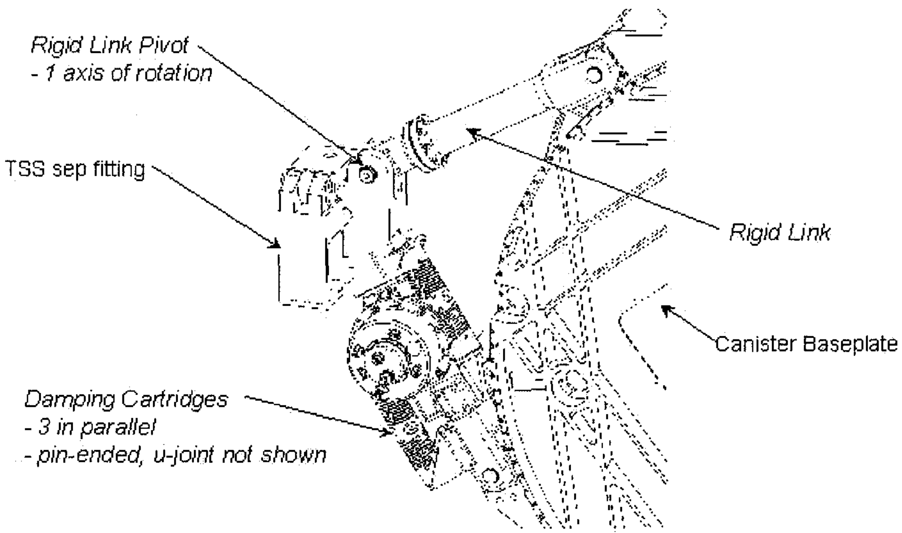

Figure 4 Bending Mode Damper Assembly

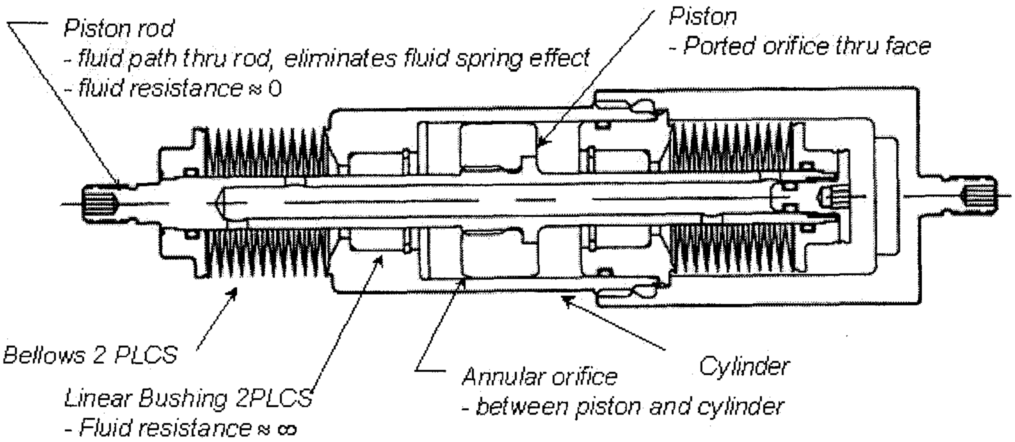

Figure 5 Damping Cartidge Cutaway